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A Wireless Data Acquisition System for Monitoring Temperature Variations in Swine Barns

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Abstract. *Increasing interest in monitoring the spatial variation of temperature at the animal level in swine finishing barns has led to the development of a new wireless data acquisition system. Previous studies used individual commercial data loggers placed in a protective container, then lowered into the animal pens. These traditional systems required significant effort to download each logger individually and to post-process the data into a time-synchronized file with all measurement points. The newly developed wireless system allows all measurement points to be simultaneously collected and logged to a single external data file. The specific project objectives include (1) develop a wireless sensor node capable of meeting the data transfer and sensor interface requirements of a swine finishing barn and (2) evaluate the performance of the wireless node through experimental testing. Each wireless node is preset with a specific ID which is logged with the sensor data to provide a definite indicator for the data's source location within the barn. The individual nodes use a high accuracy thermistor for temperature sensing and are capable of transmitting one additional analog signal and eight digital signals to the data logger. The digital inputs were commonly used to collect fan activity data for ventilation monitoring. The additional analog channel can be used for other environmental sensing or for monitoring static pressure. When powered from a single 3.6 volt, 1200 mAhr battery, the wireless nodes have a usable life of 3.5 years when transmitting at a 5-minute sampling interval. This system was successfully developed and implemented for a 4-year study of swine finishing barns.*

Keywords. *Instrumentation, Mesh network, Zigbee, Environmental monitoring, Embedded system*

Introduction

Data acquisition systems have experienced significant advances in recent years due mainly to the reduced cost and increased functionality of electronic microcontroller and microcomputer based systems (Micrologic Research, 2002). Many applications, such as monitoring indoor animal environments, have directly benefitted from this increase in technological capabilities and have enabled monitoring and data collection not previously possible. New sensors have also been developed around advanced embedded systems which allow more precise measurement of environmental parameters (Darr et al., 2007a).

Much of the recent work in animal environment data acquisition has been based around a principle of using a stationary Mobile Lab as the center point for data processing and collection (Heber et al., 2001; Schmidt et al., 2002; Wilhelm and McKinney, 2001; Xin et al., 2003; Zahn et al., 2002; Zhao et al., 2005). Sensor interface wire and gas sampling tubing is installed from the Mobile Lab to the desired measurement point in order to facilitate simultaneous multipoint data acquisition. Although this system provides an accurate means to collect and store environmental data, it has several limitations including; high cost of installation, low mobility of sampling points, and potential sensor error caused by wire degradation, moisture development, and electrical noise.

An alternative method of data acquisition in animal environments is to use wireless transmitters located at each measurement point to transfer electronic sensor data back to a common point. Wireless systems have been successfully employed in many agricultural environment applications (Nagl et al., 2003; Nichols, 2004; Hamrita and Hoffacker, 2005; Butler et al., 2006; Kim et al., 2006). Application of wireless sensing to confined animal feeding operations (CAFOs) would enhance the mobility of sensor positioning, reduce the overall cost of installation, and limit sensor error from moisture or electrical noise sources. Recent work has documented specific factors which limit wireless data transfer in production poultry layer facilities (Darr, 2007b). When compared to poultry facilities, swine finishing operations provide less modes of signal attenuation and generally maintain an open free space above the animal cages. This open design can be used to the advantage of the data acquisition system and allow for highly reliable wireless data transfer from sensors located at the animal level.

The objective of this work was to design a sensor architecture to support high density, wireless sensing of temperature within swine finishing operations. This paper will specifically address the technical design of the wireless data acquisition system including:

1. Selection and layout of wireless network topology,
2. Calculation of required transmission power based on link budget model,

3. Performance characteristics of new wireless temperature transmitter, and
4. Cost analysis of wireless data acquisition system for measurement of temperature within a swine finishing barn.

Methods

Description of Swine Finishing Facilities

The wireless data acquisition system described in this paper was developed for a 1000-head swine finishing barn. The general dimensions of the barn were 12.5 m by 60 m (Figure 1). Six individual fans were located along the west barn wall, each wired as an individual ventilation stage. Internally, the barn held 48 animal cages, each measuring 2.5 m by 5.75 m. A center aisle separated each side of 24 cages. When at full capacity, 21 animals were located in each cage. Each cage was fitted with an automatic feeding and watering system.

For the application purpose of evaluating the temporal variability within cages, one temperature sensors will be located at the junction of every two animal cages. This results in a need for 24 individual temperature sensors. Additional sensing capacity is required along the ventilation fan wall to collect fan activity data from individual vibration sensors and to monitor the pressure drop across the building wall. The combination of fan activity and pressure drop will be used to calculate the ventilation rate of each fan.

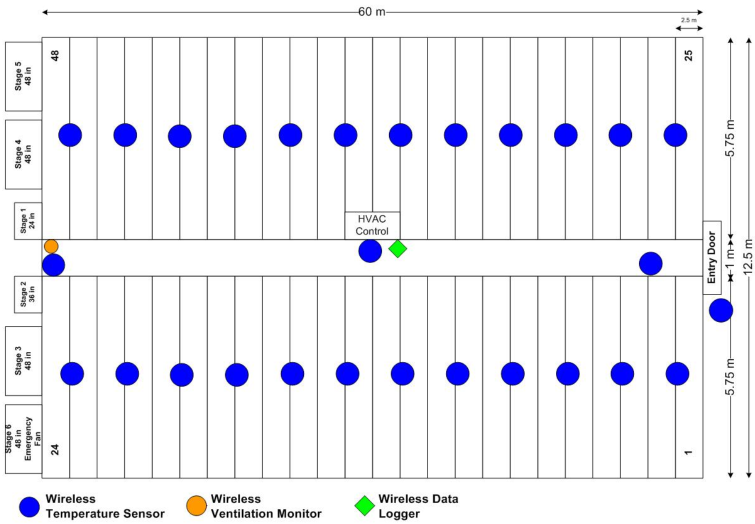

Figure 1: Schematic layout of swine finishing operation installed with animal-level wireless temperature monitors, wireless ventilation monitors, and a wireless data logging system.

Topology and Layout of Wireless Network

A wireless mesh network topology was chosen to serve as the networking platform for this project. Mesh networking technology allows for routing of individual messages through other wireless nodes. A commercial Zigbee mesh networking module (ETRX2, Telegesis) was chosen to serve as the embedded system for this project. Each individual wireless node was configured with a Zigbee module for communication as well as appropriate signal and power conditions for the attached sensor units. These particular Zigbee modules offered automatic network configuration and an adjustable transmission power from -22 to +17 dBm.

A centralized wireless data logger was located in the center of the finishing barn. This logger received sensor data wireless through the mesh network and stored the sensor values, transmission node identification number, and the data and time of reception directly to a removable flash storage card. In order for the data logger to respond to information requests from the remote nodes it was set to continuous full power mode. This full power status required that the data logger be supplied with a continuous power source, rather than a battery source.

A second full power wireless module was located near the ventilation fans. This module was connected to individual fan vibration sensors (Darr, 2007a), which provide a digital logic feedback related to the activity of the individual fan. The wireless module was also connected to the analog output signal of a differential pressure transducer through a signal conditioning and amplification circuit. The sampling interval for fan activity and barn differential pressure was set to 15 seconds. At each 15-second interval, the wireless module would transmit a single wireless message to the data logger which contained the unique node identifier, the activity status of each fan, and the magnitude of barn differential pressure. This high sampling frequency was feasible given the full power status of this module. Due to the continuous current consumption of the differential pressure transducer and the wireless module, this node was also powered from a constant, non battery source.

The combination of centralized data logger and ventilation monitor made up the backbone of the mesh network. At each measurement point, individual wireless modules were used to record the temperature at the animal level on five-minute sampling intervals. Between sampling intervals, the sensor modules entered a low power sleep mode in which they dropped entirely from the mesh network. An internal timer would wake each node at the specified five-minute interval. After a brief stabilization period, each node recorded the local temperature and transmitted the sensor values along with the source node identification number to the nearest full power node. If the in-cage sensor was most closely located to the data logger, then the sensor data, node ID, and time stamp would be directly recorded to flash memory. If the ventilation monitor was the closest node, then messages would be sent directly to the ventilation modules as an intermediary and then be forwarded wirelessly to the data logger. This enhanced ability to route messages through any full power active node increased network reliability and reduced the transmission strength requirement of each individual node.

Design of Wireless Temperature Sensor Nodes

The wireless temperature sensor nodes were developed by interfacing the ETRX2 Zigbee module with a thermistor temperature sensor (Figure 2). The thermistor was connected in series with a static resistor to provide a variable voltage output over the range of expected temperatures within the swine finishing barn. Since the thermistor bridge circuit was a purely resistive element, it would draw continuous current if connected directly to the battery supply voltage. In order to limit this quiescent current draw and reduce acquisition errors associated with changes in the battery supply voltage, the bridge circuit was powered directly from a digital output pin on the Zigbee module. The output voltage of this supply was always identical to the reference voltage of the internal analog to digital convert which eliminated scaling errors.

A ½ AA battery with a 3.6 volt, 1000 mAhr rating was used to supply operating power. The ½ AA size provided excellent packaging characteristics and the amp-hour capacity was suitable for extended operation. A general purpose header was installed to allow access to all additional analog and digital channels of the Zigbee module. Access was available to directly connect vibration based fan activity sensors to the wireless modules. An RS232 communication port was also installed to provide microcomputer interfacing capabilities and to download sensor configuration files.

An external antenna was used to maximize the wireless transmission performance. Although this increased the package cost, the antenna gain was increased over that of surface mount antennas. The remote antenna connected to the Zigbee module through a U.FL C adapter cable. The entire Zigbee module was then placed inside a PVC enclosure with only the antenna ported to the outside. A standard one-half inch cable gland was used to provide stability to the antenna as well as seal the connection between the antenna and the internal box area.

Figure 2: Manufactured wireless temperature sensor (left) and fully enclosed wireless sensor in two-inch square PVC housing with antenna stabilizer (right).

Network Mapping Structure

The ETRX2 modules employed a fully functional 802.15.4 Zigbee implementation (IEEE, 2003). This functionality allowed the individual sensors nodes to automatically form the mesh networking communication layer without any source code requirements from the user. One concern when using this automated networking procedure was whether nodes located in adjacent barns would transmit data to the correct data logger. To ensure the reliability of data logging, all nodes within a single barn were assigned a unique network ID or Pan number. Only nodes with the same Pan number will synchronize under an 802.15.4 implementation.

The data logger was programmed in software as the network Sink. This is a special designation in the 802.15.4 protocol which allows a single node to be programmed as the end point of data transfer without the actual ID of that node being known. Each of the wireless temperature sensors were then programmed to simply transmit their temperature information back to the network Sink at an appropriate time as designated by their sampling interval.

Results and Discussion

Link Budget Transmission Range Calculation

The key to successful wireless sensor networking is maintaining a positive link budget, which indicates that the power available at the receiver is greater than its internal sensitivity. The application goal is to cover the largest area possible within a CAFO with wireless sensors, thus the critical transmission distances for the wireless nodes must be identified. The wireless temperature sensors will be located at the animal level or about 2 feet from the top of the railing which separated each animal cage. The railings were made of metal bars and do not exhibit a significant shadow on the wireless antenna. The data logger will be positioned near the upper level of the barn to again increase the direct line of sight path between the wireless transmitter and the wireless data logger. Based on these conditions, free space path loss can be predicted as the main source of signal attenuation.

The link budget equation can be used to predict the maximum transmission distance for the wireless temperature nodes. If a positive link budget exists then the transmitted signal power, less losses from path loss and a reliability factor, is greater than the minimum receiver sensitivity (Equation 1).

$$\textit{Link Budget} = P_r - PL + P_t - FS \qquad (1)$$

Where:
P_r = Receiver Sensitivity (dB)
PL = System Path Loss (dB)
P_t = Power Transmitted (dB)
FS = Factor of Safety (dB)

The receiver sensitivity was defined by the ETRX2 module as -97 dBm. Previous work has shown that an appropriate factor of reliable for animal environments is 10 dBm (Darr, 2007b). At a maximum transmission power of +17 dBm the link budget or maximum acceptable path loss was -90 dBm.

Solving the Friis free space path loss equation with a known operating frequency of 2.4 GHz and estimated antenna gains of 0 dBi yields a maximum transmission range of 250 m. This value was much greater that the expected transmission range requirement and was mainly due to the high positive gain characteristics of the transmitter. Scaling back the transmission power would provide beneficial power consumption characteristics, but given the limited current use during a five-minute sampling interval the benefit of excessive reliability was greater than the potential savings in current consumption.

Temperature Measurement Error Budget

The half-bridge signal conditioning circuit used for the thermistor was composed of a 200-kohm resistor and a 100-kohm thermistor with accuracy ratings of ±0.1% and ±1%. Over the expected indoor temperature span of 10ºC to 35ºC the bridge output voltage had a change of 0.3269 volts. When measured with the internal 10-bit, 1.2-volt full-scale range analog-to-digital converter of the ETRX2 module, the sensor resolution is 0.090ºC per bit. The internal analog to digital converter was referenced against a factory trimmed reference voltage which yielded high measurement accuracy. Errors will occur though due to the accuracy ranges of the resistor and thermistor.

The maximum overall error rate will occur when the accuracy of the resistor and thermistor are out of phase. If the actual resistance is 0.1% high and the actual thermistor value is 1% low or vice versa this will cause the greatest error in the bridge voltage. When considering this case and the estimated regression provided by the expected thermistor response (Equation 2), the range of error values can be seen in Figure 3.

$$\textit{Temperature (ºC)} = 47.43885\ (\textit{volts})^2 - 118.41893\ (\textit{volts}) + 64.78829 \qquad (2)$$

Figure 3 shows a maximum measurement error of 0.43ºC at a true temperature of 30ºC under the condition where the variability in the resistor and thermistor create a positive error component. This indicates that the predicted temperature value would be higher than the actual temperature value. The standard deviation of all error conditions was 0.22ºC and the 95% confidence interval for the mean of theoretical sensor was ±0.11ºC.

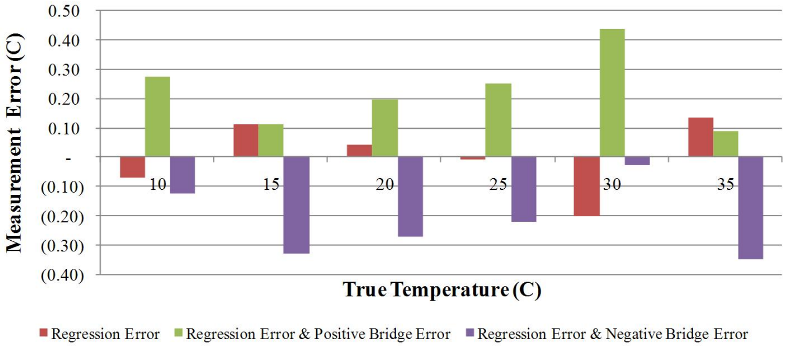

Figure 3: Maximum thermistor measurement error based from regression estimation error and interaction of thermistor and bridge resistor accuracy.

Battery Life Expectancy

The power consumption of a Zigbee node was dependent on many factors including, network structure, node routing responsibilities, transmission power, standby power efficiency, and auxiliary node components. Common Zigbee nodes, such as the ETRX2 used in this study, consume between 26 to 30 mAmps continuously when in full power mode. A common high capacity 2400-mAhr battery would only supply enough energy for 2.5 days of continuous operation. End device nodes or nodes which have no routing responsibilities can achieve much higher battery efficiency by turning the radio and microcontroller off during non-transmission times.

In order to test the power consumption of the ETRX2 wireless node a sink and data transmitter were joined into a wireless Pan. The sensor node was powered from a steady 3.0-volt supply. The positive leg of the power supply was modified to contain a precisely measured 9.8-ohm resistor in series. By monitoring the voltage drop across this inline resistor, the current consumption of the device was determined. The transmitter was configured to enter a deep sleep mode between transmissions.

Because the voltage of interest was extremely low, the data logging system was calibrated before and after the test procedures. A USB-1608, 16-bit data logger from Measurement Computing Corporation was used to monitor the voltage drop at a rate of 667 Hz. An expected transmission current of 25 mAmps would result in a voltage drop of 0.245 volts, thus the range of the USB-1608 was set to ±1 V. This provided a measurement resolution of 30.5 µVolts which related to a current resolution of 3.11 µAmps. A zero calibration was conducted by connecting the analog input on channel zero to the shared analog ground channel.

Results of the 5 second transmission interval test revealed a very repeatable pattern of high current consumption periods during transmission events and low current consumption during standby events (Figure 4). Each transmission event peaked at nearly 29 mAmps. A closer inspection of one unique transmission event shows variations in current consumption during the course of the event (Figure 4). After a short startup period, the node very quickly reached its maximum 29-mAmp current consumption during the transmission of its sensor data. It then waited for a longer period before the message was acknowledged by the receiver. The length of the waiting period was heavily dependent on the network topology, as multiple hop messages take significantly longer to be acknowledged than the single hop message presented.

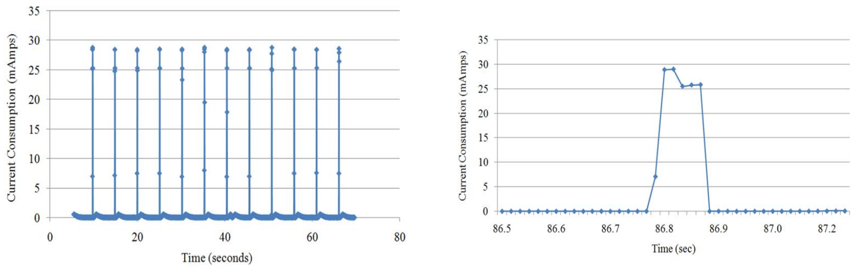

Figure 4: Variations in power consumption during transmission and sleep cycles of a wireless sensor module (left) and current consumption of a single message transmission (right).

Further analysis of the data yields an average transmission power of 27.5 mAmps with a maximum single hop transmission time of 0.1 seconds. The standby power was calculated to be 0.03 mAmps and the duration of the standby time was determined by the desired sampling period. A table of weighted current consumption data based on sampling interval shows the reduced current consumption as the sampling interval increases (Table 1).

Table 1: Cumulative current consumption of wireless sensor module based on ratio of sleep and transmission times.

Sampling Interval (sec)	Standby Current (mA)	Transmit Current (mA)	Transmit Time (sec)	Weighted Current (mA)
5	0.03	27.5	0.1	0.5794
30	0.03	27.5	0.1	0.1216
60	0.03	27.5	0.1	0.0758
180	0.03	27.5	0.1	0.0453
300	0.03	27.5	0.1	0.0392

These results can also be applied to battery life of a specific sensor node. Based on standard 3 V battery configurations of 240, 600, 1000, 1200, 1500, and 2400 mAmp-hr, the maximum operating period for the wireless node was calculated (Table 2). A standard 1000 mA-hr battery which reports sensor data on 1 minute intervals will sustain a useful life of 549.8 days.

Table 2: Expected sensor battery life based on various commercial battery power capacities.

Sensor Life for Various Battery Supplies (days)							
	Battery Power Capacity (mA-hr)						
Sampling Interval (sec)	**240**	**600**	**1000**	**1200**	**1500**	**2100**	**2500**
5	17.3	43.1	71.9	86.3	107.9	151.0	179.8
30	82.3	205.6	342.7	411.3	514.1	719.8	856.9
60	132.0	329.9	549.8	659.8	824.7	1154.6	1374.5
180	220.9	552.4	920.6	1104.7	1380.9	1933.2	2301.5
300	255.4	638.5	1064.1	1276.9	1596.2	2234.6	2660.3

An experimental test was conducted to validate the battery life expectancy. When operated at five-minute sampling intervals with a 1000-mAmp-hr battery, the life expectancy was 1064 days or 306,432 message transmissions. An accelerated life test was conducted by increasing the sampling frequency to three seconds, which allowed for the 306,432 messages to be transmitted within only 10.6 days. Since the current during standby was known to be extremely low, this method can provide an accurate estimation of actual battery life. Results yielded a total battery life of 12.75 days or 367,200 message transmissions before a significant change in battery voltage occurred (Figure 5).

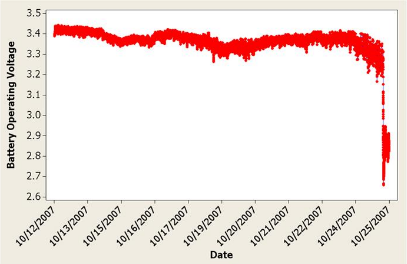

Figure 5: Battery voltage during accelerated life testing of wireless temperature sensor.

Data Processing Methodology

Data sent from the wireless temperature sensor is received by the data logger through an RS232 connection. The data packet from the remote sensor contains a string of information including the node serial number, the battery voltage level, an incrementing transmission counter, the value of all 12 digital I/O pins, and the value of both analog to digital conversion registers. An example of this message format is:

NDATA:000D6F00000DDC96,2896,CD,0FF7,0278,0260 (3)

Where: Serial ID $=000D6F00000DDC96_{16}$
Battery Voltage $= 2896_{10}$
Transmission Counter $= CD_{16}$
Digital I/O Register $= 0FF7_{16}$
Analog Channel 1 Value $= 0278_{16}$
Analog Channel 2 Value $= 0260_{16}$

The serial number identified the exact location of the data in the barn. The battery voltage was used directly as an indicator that battery replacement was required. The transmission counter was used during post processing to verify the message reception rate. If the any steps in the transmission counter data are greater than one integer, then this indicated that the remote transmitter sent a message, received an affirmative reception reply, but the message was not logged. An indication of data quality was attained by tracking the continuity of the transmission counter of each node during the course of a study.

The digital I/O register allowed access to the current state of each of the 12 digital I/O pins. A bitwise conversion was performed to deduce each individual pin into its bit state. The analog channel values represent the actual voltage level at the analog to digital converter, rather than the digital count of the result register. For the Channel 1 example shown above, 0278_{16} is equivalent to 0632_{10} or 0.632 volts. Based on the second order calibration equation presented previously (Equation 2), the temperature was 24.4ºC.

Cost Analysis

The total cost of each wireless temperature sensor module was $72.19 for production runs greater than 100 units. The circuit board assembly was performed by Datran Corporation (Broken Arrow, OK) and pricing included parts not listed individually as well as full board manufacturing. Opportunities exist in reducing the unit cost by scaling down to a lower power transmitter and using a surface mount embedded antenna rather than the externally mounted antenna. With these modification, a potential price point of $50.39 per 100 units.

Table 3: Unit cost of production for 100 wireless temperature sensor units.

Description	Unit Cost
Circuit Board Assembly	$19.00
ETRX2-PA Wireless Transmitter	$30.44
2.4 GHz Antenna	$5.45
Antenna Cable	$8.91
Battery Holder	$0.63
1/2 AA Battery, 1000 mAhr	$3.76
Enclosure	$4.00
Total Cost	$72.19

The cost for the data logger is slightly higher at $262.19 per unit. The data logger requires two additional components in a NEMA 4 sealed enclosure and a separate embedded controller cable of logging data to a removable flash card. Similar pricing exists for the ventilation monitoring node. Although a data logging embedded controller is not required, a differential pressure sensor must be added in order to calculate and accurate ventilation rate estimate.

Conclusion

Wireless temperature sensors, developed under the 802.15.4 Zigbee protocol, were found to be suitable for monitoring in CAFO environments and provided enhancements over current CAFO data acquisition methods. The nodes utilized ETRX2 Zigbee modules with high transmission gain characteristics that allowed message transmission up to 250 m. When operated as an end device and allowed to enter a low-power sleep mode between message transmissions, the nodes were shown to last several years while operating from a single moderate size battery. The accuracy of the temperature measurement was static over time and based on the accuracy of the thermistor and resistor components. Changes in battery voltage were isolated from impacting measurement accuracy. Based on all known accuracy parameters, the sensor error was found to be below ±0.11ºC. At a mass produced cost of $50.39 each, the sensors also provide a lower-cost measurement solution that allow more dense, intensive sampling of CAFO environments.

References

Butler, Z., P. Corke, R. Peterson, and D. Rus. 2004. Virtual fences for controlling cows. In: *Proceedings of the 2004 IEEE International Conference on Robotics and Automation*, New Orleans, LA, USA, April 26–May 1, pp. 4429–4436.

Darr, M. J., L. Zhao, J. Ni, and C. Gecik. 2007a. Robust sensor for agricultural ventilation fan monitoring. *Transactions of the ASABE*. 50(3): 1019-1027.

Darr, M. J. 2007b. Advanced embedded systems and sensor networks for animal environment monitoring. PhD Dissertation. Columbus, OH: The Ohio State University, Department of Food, Agricultural and Biological Engineering.

Hamrita, T. K., and E. C. Hoffacker. 2005. Development of a "smart" wireless soil monitoring sensor prototype using RFID technology. *Applied Engineering in Agriculture* 21(1): 139−143.

Heber, A. J., J. Q. Ni, B. L. Haymore, R. K. Duggirala, and K. M. Keener. 2001. Air quality and emission measurement methodology at swine finishing buildings. *Transactions of the ASAE.* 44(6): 1765-1778.

IEEE, 2003. Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs). IEEE Standard 802.15.4. The Institute of Electrical and Electronics Engineers Inc., 345 East 47th Street, New York, USA.

Kim, Y., R. G. Evans, W. Iversen, and F. J. Pierce. 2006. Instrumentation and control for wireless sensor network for automated irrigation. ASABE Paper No. 061105. St. Joseph, Mich.: ASABE

Micrologic Research. 2002. Overview of the Microcontroller Market. Phoenix, AZ.

Nagl, L., R. Schmitz, S. Warren, T. S. Hildreth, H. Erickson, and D. Andresen. 2003. Wearable sensor system for wireless state-of-health determination in cattle. In: *Proceedings of the 25th IEEE EMBS Conference,* Cancun, Mexico, September 17–21.

Nichols, M. H. 2004. A radio frequency identification system for monitoring coarse sediment particle displacement. *Applied Engineering in Agriculture.* 20(6): 783−787.

Schmidt, D. R., L. D. Jacobson, and K. A. Janni. 2002. Continuous monitoring of ammonia, hydrogen sulfide, and dust emissions from swine, dairy, and poultry barns. ASAE Paper No. 024060. St. Joseph, MI.: ASAE.

Wilhelm, L. R., and D. B. McKinney. 2001. Environmental measurements in production swine facilities. *Applied Engineering in Agriculture.* 17(5): 669-675.

Xin, H., Y. Liang, A. Tanaka, R. S. Gates, E. F. Wheeler, K. D. Casey, A. J. Heber, J. Q. Ni, and H. Li. Ammonia Emissions from U.S. Poultry Houses: Part I – Measurement System and Techniques. In: *Proc. Third International Conference on Air Pollution from Agricultural Operations*. Oct 12-13, 2003. Raleigh, NC.

Zahn, J., A. E. Tung, and B. A. Roberts. 2002. Continuous ammonia and hydrogen sulfide emission measurements over a period of four seasons from a central Missouri swine lagoon. ASAE Paper No. 024080. St. Joseph, MI.: ASAE.

Zhao, L., T. T. Lim, H. Sun, and C. A. Diehl. 2005. Particulate matter emission from an Ohio belt-battery layer barn. ASAE Paper No. 054010. St. Joseph, MI.: ASAE.